REPORT NO. 193

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AN APPLICATION OF INTERCOUPLED-TRANSMISSION-LINE-AMPLIFIER

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Chushin Afuso

November 1, 1965

DEPARTMENT OF COMPUTER SCIENCE · UNIVERSITY OF ILLINOIS · URBANA, ILLINOIS

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SUMMARY

An attempt has been made to use an intercoupled transmission line with tunnel diodes as a pulse amplifier for driving, in particular, high-speed diode logic circuits. For this purpose hot-electron diodes were used.

The voltage swing of the amplifier is limited by the characteristics of tunnel diodes. It is not large enough to drive hot-electron diodes without bias. Hence it is necessary to bias the diodes properly.

A satisfactory result was obtained for the case where overall voltage gain, including voltage attenuation due to internal resistance of hot-electron diodes, was less then unity.

Further trials to obtain a higher voltage gain have been done. The results were not satisfactory, however.

1. INTERCOUPLED TRANSMISSION LINE AS A PULSE AMPLIFIER (see Fig. 1)

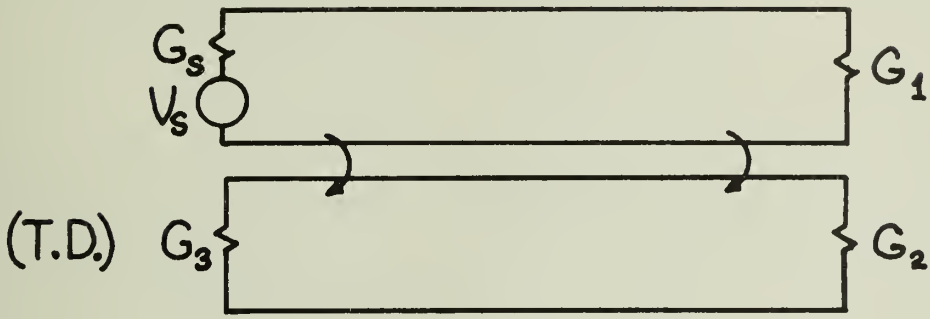


Figure 1. Intercoupled Transmission Line

In order for an intercoupled transmission line to serve as a reflectionless pulse amplifier, the following conditions must be satisfied according to H. Guckel*

$$G_2 = -G_3$$

$$G_1 = \frac{G_0 G_2 - (G_0^2 - G_m^2)}{G_2 - G_0}$$

where

$$G_0 = \frac{Z_0}{Z_0^2 - Z_m^2}$$

$$G_m = \frac{Z_m}{Z_0^2 - Z_m^2}$$

* Guckel, H., "Properties of Intercoupled Transmission Lines Terminated by Negative Resistance Elements with Applications to Tunnel Diode Pulse Circuits." Department of Computer Science, University of Illinois, Urbana, Illinois. Report #143 (June, 1963).

Z_0: the characteristic impedance of each line without coupling, symmetry of the configuration being assumed.

Z_m: the mutual impedance. Under these conditions the voltage transfer K, the current transfer K_i, G_2, and G_1 have the characteristics as functions of G_0 as shown in Fig. 2.

Region I: $|K|$, $|K_i| < 1$.

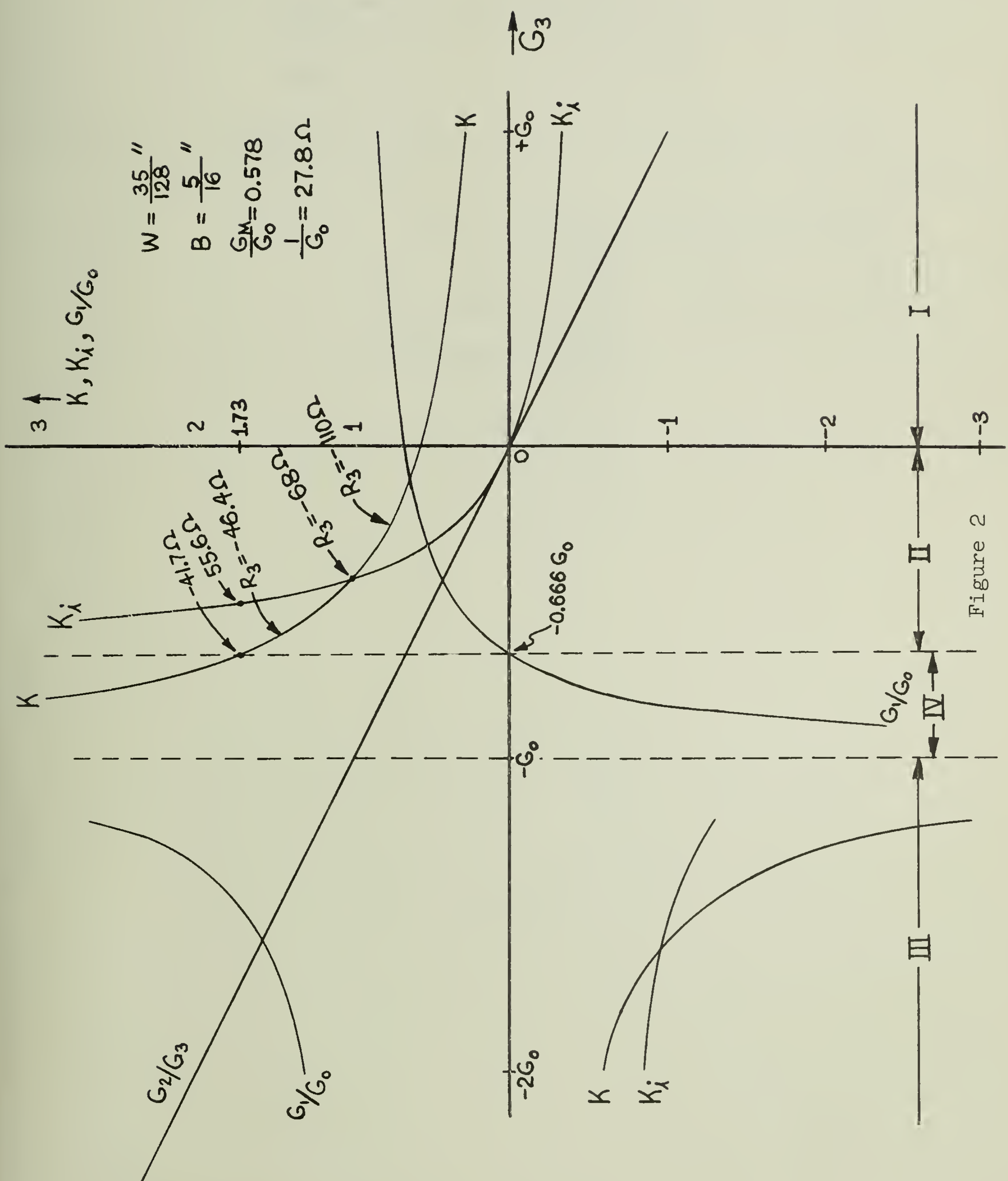
Region II: K, $K_i > 1$ is possible.

Region III: Although $|K|$, $|K_i| > 1$ is possible, it is not realizable because of instability.

Region IV: $|K|$, $|K_i| > 1$ is possible. $G_3 < 0$ and $G_1 < 0$, i.e., two negative resistance terminations are required.

Therefore only Regions II and IV have useful gain.

As Region IV requires two negative resistors, only Region II has been considered.



K, K_i, G1/G0
G3
W = 35/128″
B = 5/16″
GM/G0 = 0.578
1/G0 = 27.8 Ω
R3 = -110 Ω
R3 = -68 Ω
R3 = -46.4 Ω
55.6 Ω
-41.7 Ω
-0.666 G0
+G0
-G0
-2G0
1.73
K
K_i
G1/G0
G2/G3
I
II
III
IV

Figure 2

2. CHARACTERISTICS OF HOT-ELECTRON DIODES

Figure 3 shows the characteristics of hot-electron diodes. From the figures, the incremental resistances are about:

35 ohms at I = 2 ma for hpa 2006

30 ohms at I = 2 ma for hpa 2103

40 ohms at I = 2 ma for hpa 2105

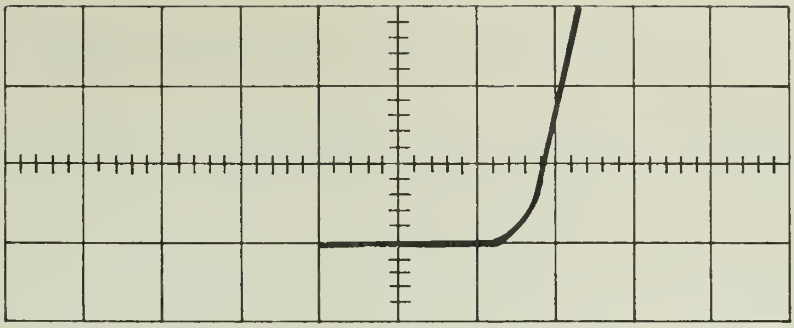
To drive these diodes with the output of the amplifier which has as its output at most 200 mv, it is necessary to bias the diodes.

The necessary bias voltages are about:

460 mv for hpa 2006

260 mv for hpa 2103

260 mv for hpa 2105



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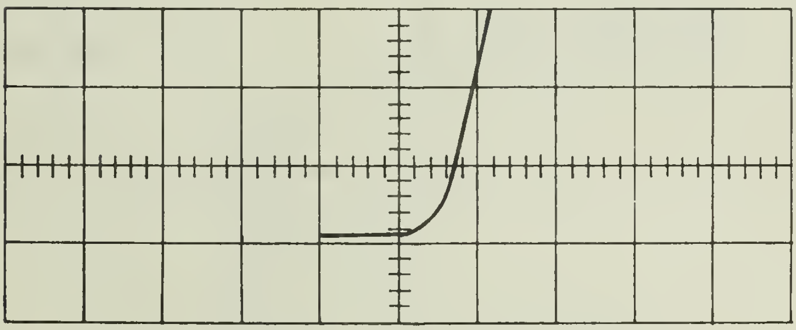

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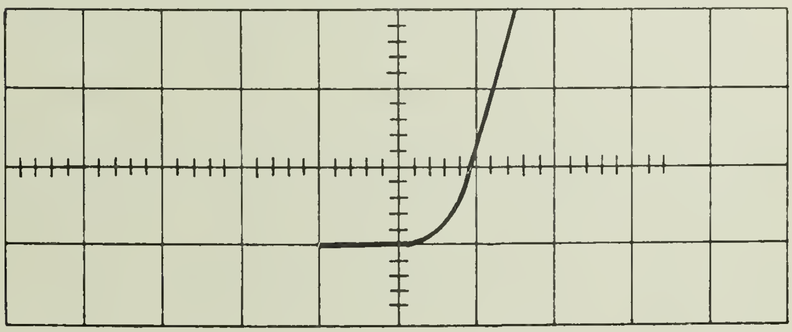
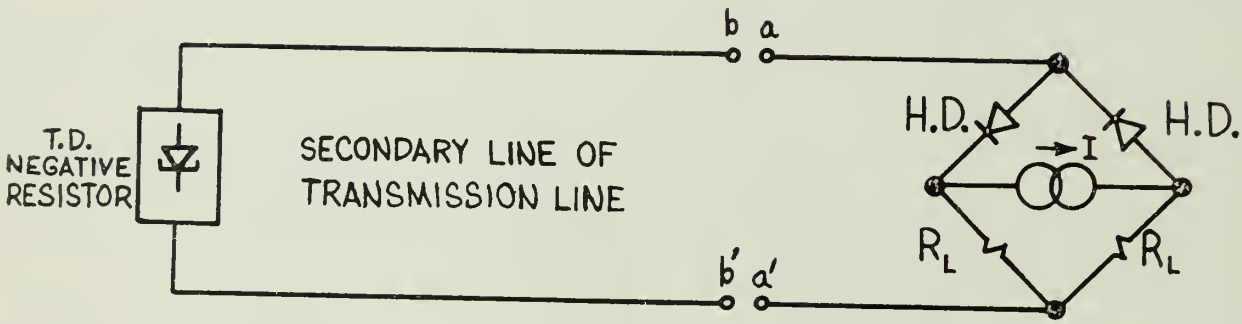


3c

Figure 3

3. BIAS CIRCUIT FOR HOT-ELECTRON DIODES

The circuit shown in Figure 4 has been found useful.



I is the bias current source

Figure 4. Bias Circuit for Hot-Electron Diodes

When two diodes are the same and the the two resistors are also the same, the bridge so formed is always balanced, i.e., regardless of the value of I there is no potential difference due to I between a and a'. Hence the connection of these terminals to the secondary of the transmission line b and b' does not affect the bias of the tunnel diode circuit that is connected at the other end of the line.

Only one diode and one resistor are used for the logic circuit. Another pair is connected: (1) to realize a linear resistance as seen from a and a', and (2) to balance the bridge.

Since the internal resistance of a hot-electron diode is not negligible in comparison with the load resistance R_L, there is voltage attenuation.

One might think that the load resistance can be increased so that the voltage drop due to the internal resistance of diode may be neglected. However, this is not so. As the voltage swing is limited by the characteristic of the tunnel diode, increasing the load resistance automatically makes the current small, so that the incremental internal resistance of diode at the lower value of the current should be taken. As seen in Figure 3, the incremental resistance starts to increase at about I = 1 ma. Thus increasing the load resistance does not improve the situation.

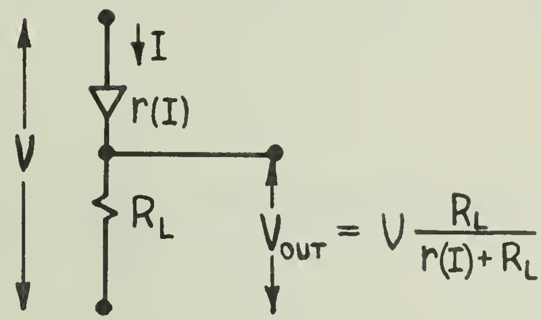


Figure 5. Attenuation Due to the Internal Resistance of the Diode

Another way to reduce the voltage attenuation is to use several diodes in parallel. However, this does not improve the situation either, unless the tunnel diodes, which realize negative resistance, have a high enough current capacity for the currents through each hot-electron diode to remain the same. When tunnel diodes with high current capacity are used a difficulty arises in obtaining stability. This will be discussed later.

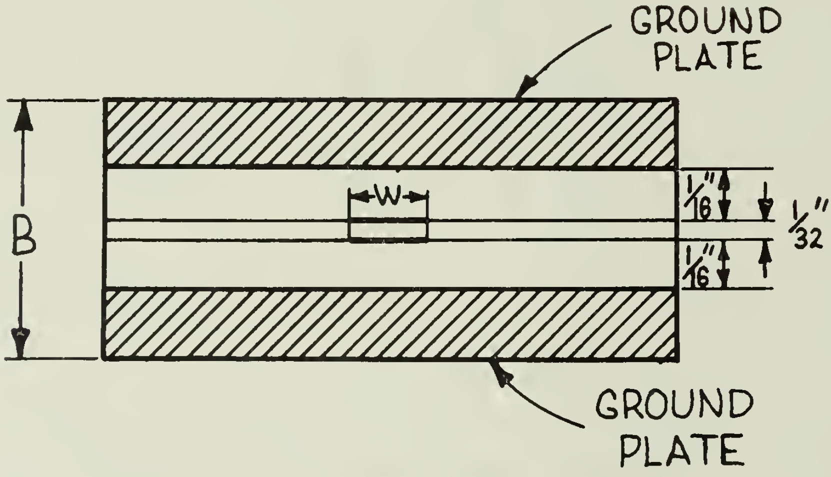
Therefore, as long as commercially available hot-electron diodes are used with this amplifier, voltage attenuation is not negligible.

4. DESIGN PROCEDURE OF THE INTERCOUPLED TRANSMISSION LINE AMPLIFIER

According to Figure 2, in order to obtain specific values of K and K_i the values of G_3/G_0 are restricted.

There are two ways to attain proper values of G_3/G_0: (a) given G_3 (i.e., given negative resistance), adjust G_0, i.e., adjust the structure of the transmission line; (b) given G_0 (i.e., given a transmission line), adjust G_3, i.e., the negative resistance.

In case (a), the geometrical size of the transmission line must be well controlled. This is impossible without special precision tools. Therefore a fixed transmission line is taken, i.e., case (b). The geometrical size is shown in Fig. 6.



$$W = \frac{35}{128} \text{ inch, } B = \frac{5}{16} \text{ inch}$$

Material: Rexolite 2200, E_r = 2.72

Figure 6. Geometrical Size of the Intercoupled Transmission Line

For these values,

$$\frac{1}{G_0} = 27.8 \text{ ohms}$$

$$\frac{G_m}{G_0} = 0.578$$

Values of G_1, K, K_i are shown in Fig. 2.

As nonuniformity of the line width ΔW is determined by the constructing process, small values of W increase $\Delta W/W$ and hence are not desirable.

To adjust the effective negative resistance R_3, a shunt passive resistance R is connected as shown in Fig. 7.

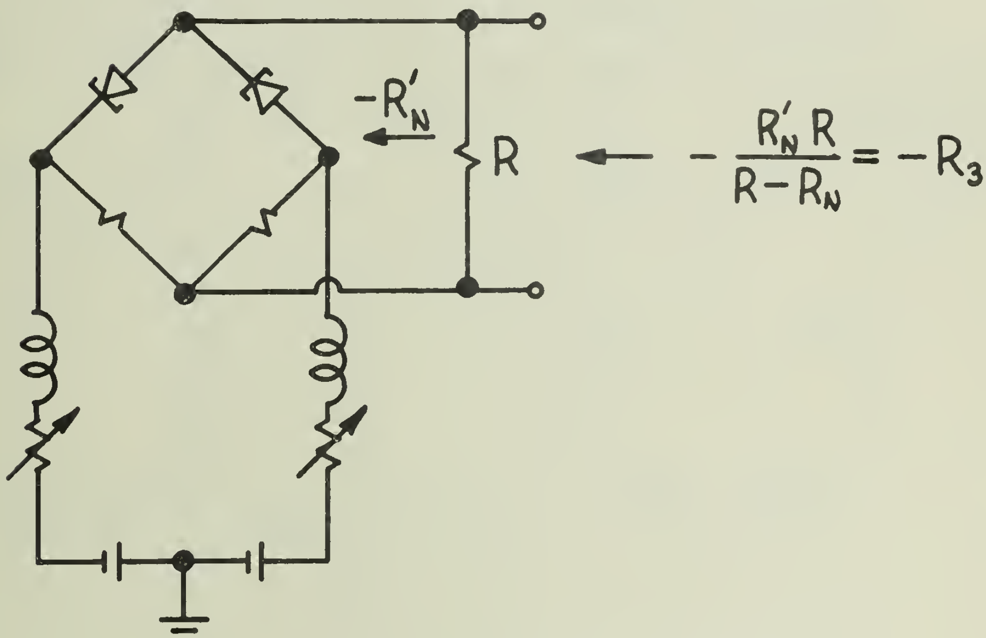


Figure 7. Adjusting Negative Resistance

5. RESULTS OF THE EXPERIMENTS

Tunnel Diodes: MX-1081 (Micro State Electronics Corporation), GaAs diode

$$I_p = 1 \text{ ma}$$

$$-R_n = -130 \text{ ohms}$$

$$C = 3 \text{ to } 5 \text{ pf}$$

$-R_n'$ (negative resistance of the pair) = -110 ohms

Hot-electron diodes: hpa-2105

$R = \infty$ (no shunt resistance), instead 240 Ω is connected to the load in shunt for matching. Figure 8 shows the circuits which are connected to the secondary line.

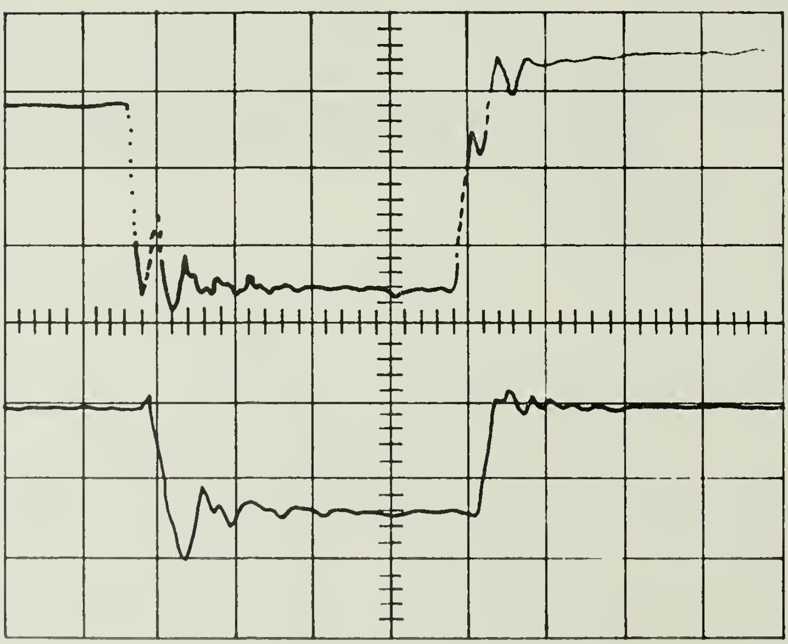
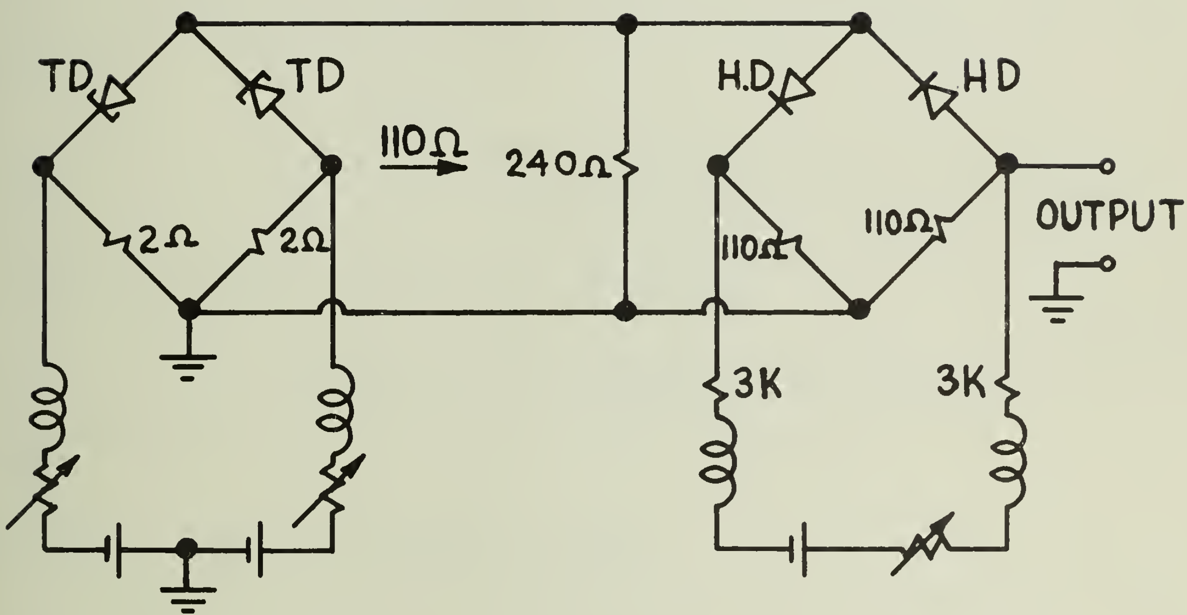


Figure 8. Secondary Line

The observed waveforms are shown in Fig. 9.



Upper trace: Input (primary line) negative pulse, 100 mv/div
Lower trace: Output, negative pulse 50 mv/div
Time: 5 nsec/div

Figure 9. Waveforms of Input and Output

The total output voltage across the secondary line was about 150 mv. Therefore the voltage transfer K is approximately 0.6, while the theoretical value is about 0.75 by Fig. 2. The operation is stable. The voltage transfer is too small for practical use.

Tunnel diodes: RCA 1N3128, Ge diode

$$I_p = 5 \text{ ma}$$

$$-R_n \sim -20 \text{ ohms}$$

$$C \sim 13 \text{ pf}$$

$$-R_n' = -17 \text{ ohms}$$

$R_3 = 68$ ohms, single resistor without hot-electron diodes

$$R = 22 \text{ ohms}$$

The result was satisfactory. The voltage transfer $K \sim 1.0$ was observed and this agrees with the theoretical value.

To obtain useful voltage gain, $R_3 = 51$ ohms, -47 ohms, -43 ohms with appropriate values of R were tried. The results were unsatisfactory.

These values are all supposed to be in Region II.

6. SOME CONSIDERATIONS

When the results are unsatisfactory there are two types of phenomenon on the secondary line of the amplifier: (a) oscillation, and (b) bistable mode. Although these have not been analyzed in detail, it would seem that they are caused by the failure to satisfy the stability conditions of the system.

In the original thesis by H. Guckel there is no general examination of the stability. Instead he treats the stability only for the case where the source impedance $Z_s = 0$. Therefore it is not assured that one can obtain a satisfactory result in general, even if the matching conditions for reflectionless transmission are satisfied.

When the amplifier is used in a practically useful system, it is rather unusual to have $Z_s = 0$. Therefore the stability conditions must be examined for the general case, and design criteria must be established accordingly. However, this is not intended here.

It is reasonable to think that when ac stability is not satisfied there is an oscillation, and when dc stability (stability at zero frequency) is not satisfied there is a bistable mode of operation.

Difficulty with High Current Tunnel Diodes

When high current is required, the tunnel diode must have a high current capacity, i.e., a high peak current.

Since the voltage swing of the negative resistance region is characterized by the material of the tunnel diode, as I_p increases R_n decreases.

The stability condition, for the tunnel diode circuit is

$$R_n > r + R_s > \frac{L + L_s}{R_n C}$$

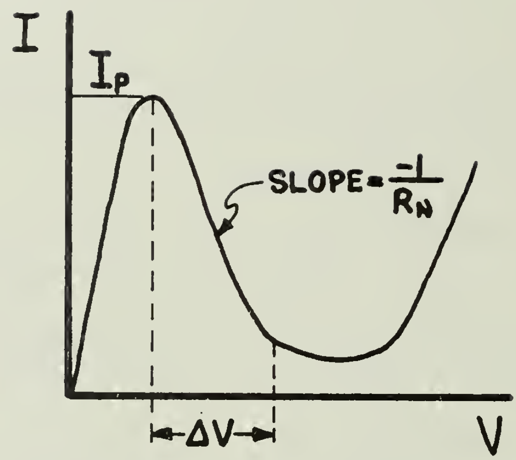


Figure 10. Characteristics of Tunnel Diode

Ls, Rs, C, and -Rn are equivalent circuit parameters and r and L form the external impedance connected to the tunnel diode as shown in Fig. 11.

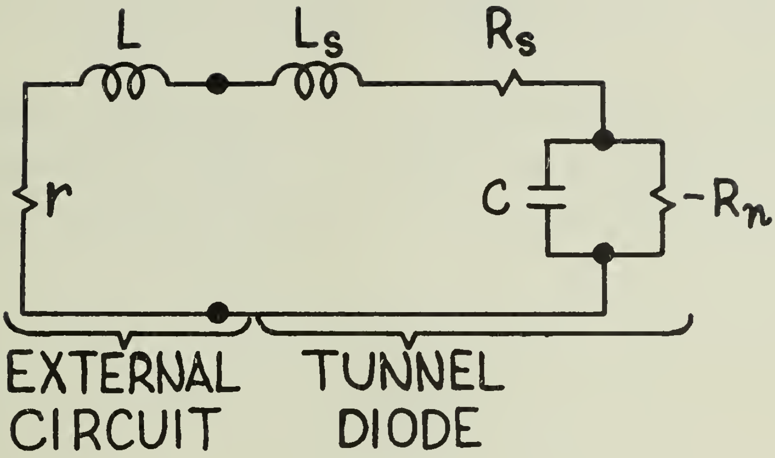


Figure 11. Equivalent Circuit for the Tunnel Diode in the Negative Resistance Region

If R_n is sufficiently low that

$$R_n < \frac{L + L_s}{R_n C} ,$$

then the stability condition is never satisfied. This situation is not unusual. For example, for RCA 1N3128

$$R_n = -17 \sim -23 \text{ ohms}$$

$$L_s \sim 0.6 \text{ nh}$$

$$C = 4.5 \text{ pf} \sim 13 \text{ pf}$$

(In the manual C_{max} = 15 pf is specified. Six out of ten diodes have C ~ 5 pf.)

$L = 1 \sim 2$ nh is easily obtained. Suppose $L = 1$ nh, $R_n = -17$ ohms, $C = 5$ pf, then

$$\frac{L + L_s}{R_n C} = \frac{1.6 \quad 10^{-9}}{17 \times 5 \times 10^{-12}} = \frac{160}{1.7 \times 5} \cong 19 \text{ ohms} > 17 = R_n$$

The large junction capacitance C may be desirable from this point of view. However, the existence of capacitance violates the matching conditions of the amplifier. Therefore there is a practical limitation on it.

REFERENCE

Guckel, H., "Properties of Intercoupled Transmission Lines Terminated by Negative Resistance Elements with Applications to Tunnel Diode Pulse Circuits." Department of Computer Science, University of Illinois, Urbana, Illinois. Report #143 (June, 1963).

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